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International Study of Objectively-measured Physical Activity and Sedentary Time with Body Mass Index and Obesity: IPEN Adult Study

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Abstract

Background—Physical activity (PA) has been consistently implicated in the etiology of obesity, while recent evidence on the importance of sedentary time remains inconsistent. Understanding of dose-response associations of PA and sedentary time with overweight and obesity in adults can be improved with large-scale studies using objective measures of PA and sedentary time. The purpose of this study was to examine the strength, direction and shape of dose-response

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associations of accelerometer-based PA and sedentary time with BMI and weight status in 10 countries, and the moderating effects of study site and gender.

Methods—Data from the International Physical activity and the Environment Network (IPEN) Adult study were used. IPEN Adult is an observational multi-country cross-sectional study, and 12 sites in 10 countries are included. Participants wore an accelerometer for seven consecutive days, completed a socio-demographic questionnaire and reported height and weight. In total, 5712 adults (18–65 years) were included in the analyses. Generalized additive mixed models, conducted in R, were used to estimate the strength and shape of the associations.

Results—A curvilinear relationship of accelerometer-based moderate-to-vigorous PA and total counts/minute with BMI and the probability of being overweight/obese was identified. The associations were negative, but weakened at higher levels of moderate-to-vigorous PA (>50 min/day) and higher counts/minute. No associations between sedentary time and weight outcomes were found. Complex site- and gender-specific findings were revealed for BMI, but not for weight status.

Conclusions—Based on these results, the current Institute of Medicine recommendation of 60 minutes/day of moderate-to-vigorous PA to prevent weight gain in normal-weight adults was supported. No relationship between sedentary time and the weight outcomes was present, calling for further examination. If moderator findings are confirmed, the relationship between PA and BMI may be country- and gender-dependent, which could have important implications for country-specific health guidelines.

Keywords

obesity; accelerometers; exercise; sitting

Introduction

In recent decades, the prevalence of overweight and obesity has increased in developed and most developing countries (1). It has been argued that this represents an ‘obesity pandemic’, which may be responsible for serious medical, psychological, social and economic consequences, including increased population rates of hypertension, type 2 diabetes, and dyslipidemia, decreased quality of life, higher rates of depression and low self-esteem, and higher health care utilization and costs (2).

Physical activity (PA) is an important contributor to energy expenditure and a major pillar for population-wide weight control strategies (3). It has been suggested that high volumes of sedentary time may be associated with increased risk of overweight and obesity, independently of PA (4,5) but the currently available study results are inconsistent and more high-quality studies are needed to confirm the importance of sedentary time for weight control (6,7). Maintaining PA, limiting sedentary time and having a normal weight can jointly affect other health outcomes, including cardiovascular diseases, type 2 diabetes and some cancers (3,5,8).

Next to the need for more evidence on the relationship between sedentary time and weight outcomes, the specific dose-response associations of PA and sedentary time with overweight and obesity remain to be determined. To address this issue, international PA and sedentary time data are needed, preferably employing objective exposure measures (9). Although many countries conduct population-based surveys as part of health surveillance systems, sedentary time is usually not included, and the use of different assessment methods across studies makes it difficult to compare results worldwide (9,10). Most population-based and epidemiological studies have used self-report questionnaires to assess PA (9,10). Some of these questionnaires have been extensively validated, particularly the International Physical Activity Questionnaire (11–13), but objective measurements using small, wearable devices (accelerometers) are needed to more accurately capture volumes and intensities of PA and sedentary time. The International Physical Activity and the Environment Network (IPEN) Adult study was conducted in 12 countries worldwide, using a comparable study design (14) and can address some of the shortcomings of prior studies.

The first aim was to examine the strength, direction and shape of the dose-response associations of objectively-assessed PA and sedentary time with Body Mass Index (BMI) and weight status. Second, because associations between PA, sedentary time and overweight/obesity can be culture- and gender-dependent (15), the moderating effects of study site and gender were examined.

Methods

Study design

IPEN Adult is an observational epidemiologic multi-country cross-sectional study, including 17 city-regions (hereafter, sites) located within 12 countries: Australia (Adelaide), Belgium (Ghent), Brazil (Curitiba), Colombia (Bogota), Czech Republic (Olomouc, Hradec Kralove), Denmark (Aarhus), China (Hong Kong), Mexico (Cuernavaca), New Zealand (North Shore, Waitakere, Wellington, Christchurch), Spain (Pamplona), the United Kingdom (Stoke-on-Trent) and the United States (Seattle, Baltimore). For the present analyses, 10 countries (12 sites) that collected objective data using Actigraph accelerometers were included, since no accelerometer data were collected in Australia and a different accelerometer type that provided incompatible data was used in New Zealand.

Study participants were recruited in neighborhoods chosen to maximize variance in neighborhood walkability and income. For selection of neighborhoods, all countries but one (Spain) used a neighborhood walkability index that was measured objectively with GIS data. Further details for each country can be found elsewhere (14). The walkability index was derived as a function of at least two of these variables: net residential density, land use mix and intersection density. In four countries, retail floor area ratio was also included as a proxy for pedestrian-oriented design. The method used to create the walkability index is described in more detail elsewhere (16,17). Each country used the walkability index to select higher- and lower-walkability areas and household-level income data from the census to select higher- and lower-income areas. The neighborhood-selection techniques employed in each country can be found in Table 1 and elsewhere (14). In all countries, the selection procedure resulted in an equal number of neighborhoods among four types (quadrants) stratified as follows: high-walkable/high-income, high-walkable/low-income, low-walkable/high-income, and low-walkable/low-income.

Participant recruitment

The participant recruitment strategy used in IPEN Adult was a systematic selection of participants living in the predefined neighborhoods. Random samples of adults living in the selected neighborhoods were contacted and invited to wear an accelerometer for objective PA assessment. Three countries recruited and conducted data collection by phone and mail/online surveys; six countries visited participants in person to deliver study materials (Table 1). In Hong Kong, intercept interviews were conducted in residential areas where individual addresses were not available. Study dates ranged from 2002 to 2011. Recruitment age ranged from 16 to 94. Because only three countries had a wider age range (Table 1), only adults aged 18–66 were included in our analyses. In six countries, participants were recruited across seasons to control for variations in weather that may affect PA. In the other countries, participants were recruited equally across the quadrants by season. Further details on the participant recruitment techniques and response rates can be found elsewhere (14).

In this paper data from 12 sites (total N= 9065) in 10 countries were included. Of these 9065 participants, 3100 did not have accelerometer data and 253 had fewer than four valid days of data, yielding a final sample of 5712. In general, when compared to participants who did not wear accelerometers or had fewer than four valid days of accelerometer data, those who had at least four valid days were more likely to be older ($p<.001$), married ($p<.001$), employed ($p=.014$) and overweight ($p=.036$). No significant differences were found for gender, educational attainment, BMI (kg/m^2), being obese vs. non-obese, neighborhood socio-economic status and objectively-assessed neighborhood walkability. The socio-demographic characteristics of the sample with valid accelerometer data by study site are presented in Table 2.

Quality control

All investigators completed the San Diego State University Institutional Review Board training, and met the NIH Fogarty International Center and their own country's ethics requirements. All participants provided informed consent for participation in their country-level study. Participant confidentiality for pooled data was maintained by de-identification using numeric identification codes. For data transfer, a secure file sharing system was used. Survey data (demographics and BMI) were assessed for completeness by the study sites and double-checked by the Coordinating Center in San Diego. Accelerometer data were provided in pre-processed format (i.e. DAT or CSV files) to the Coordinating Center where trained researchers screened all data using MeterPlus software version 4.3. (www.meterplussoftware.com). Protocols for screening data to identify valid wearing time were developed for different Actigraph models, methods of deployment, available documentation of wearing time, and cultural differences in activity patterns (18).

Measures

Body Mass Index—Participants reported height and weight (six countries) or were measured in person using standard techniques (four countries), and BMI (kg/m^2) was calculated. Previous studies showed that self-reported and objectively measured BMI are highly correlated and that BMI can be used as a proxy measure for adiposity in large-scale studies (19). Both BMI (continuous) and weight status (dichotomous) were examined as outcomes. Weight status was defined as being non-overweight (BMI ≤ 24.9 kg/m^2) versus being overweight and obese (BMI ≥ 25.0 kg/m^2). Due to multicollinearity with study site, not mode of collection but only study site was entered as a covariate in the statistical analyses.

Objectively-assessed PA and sedentary time—Mean minutes/day of moderate-to-vigorous intensity physical activity (MVPA), mean minutes/day of sedentary behavior and mean counts/minute were assessed objectively using accelerometers. Reliability and validity of accelerometers have been documented extensively (20–22). In three countries, accelerometers were mailed to participants; in others they were hand-delivered. Participants were asked to wear the accelerometer above the right hip for seven consecutive days during waking hours and to remove it only for water activities (e.g. swimming, bathing). Different models of the ActiGraph accelerometer (Pensacola, FL) were used in the study, including the 7164/71256 models, GT1M, ActiTrainer and GT3X models. Because previous studies do not provide univocal results on whether MVPA and sedentary time data of different ActiGraph models can be pooled (23–26) and no definite solution is available yet to take into account the use of different ActiGraph models in statistical analyses, it was decided to control for ‘Actigraph model’ in all analyses.

Accelerometer data were collected in (or aggregated to) one-minute epochs. Non-wear time was defined as 60 minutes or more of consecutive zero counts. Only data of participants with at least 10 wearing hours for at least four days were included in the analyses. Of these participants 84.8% had at least one weekend day of wearing time because they had 6 or more valid days of accelerometer wearing. Mail days and participants with data indicating device malfunction were excluded. Counts/minute were converted into minutes of sedentary time (≤100 counts/min), moderate- (1952–5724 counts/min), and vigorous-intensity (5725+ counts/min) PA (21,27,28). Because total counts/min are more appropriate measures of energy expenditure than sedentary time and MVPA (since these are categorized based on cut points), accelerometer counts/min were also used as an outcome measure in the present paper. Across countries, the number of adults wearing accelerometers ranged from almost 200 to over 2000 (18).

Socio-demographic characteristics—Age, gender, educational level, work status and marital status of the participants were assessed. While types of education varied by country, all country data could be categorized into ‘university degree’, ‘high school diploma’ and ‘less than high school diploma’. Marital status was dichotomized into married or living with a partner versus not. These socio-demographic variables were included as covariates in all statistical models.

Data analyses

Descriptive statistics were computed for the whole sample with at least four valid days of accelerometer data and by study site. Associations of accelerometer-based PA and sedentary time with BMI and weight status were estimated using generalized additive mixed models (GAMMs; 29). GAMMs can model data following various distributional assumptions, account for dependency in error terms due to clustering, and estimate complex, dose-response relationships of unknown form (29). Preliminary analyses based on residuals and Akaike's information criterion (AIC, a measure of model fit) indicated that for the continuous measure of BMI, GAMMs with Gamma variance and logarithmic link functions would be most appropriate. The reported antilogarithms of the regression coefficient estimates of these GAMMs represent the proportional increase in BMI (kg/m2) associated with a unit increase in the correlates. For dichotomous weight status indicators (non-overweight vs. overweight/obese), GAMMs with binomial variance and logit link functions were used. The reported antilogarithms of the regression coefficients of these models represent odds ratios of being overweight or obese.

Main-effect GAMMs estimated the dose-response relationships of objectively-measured PA and sedentary time with BMI and weight status, adjusting for study site, socio-demographic covariates, accelerometer wear time and administrative-unit-level socio-economic status. Separate models were estimated for (1) MVPA and sedentary time and (2) average counts/minute. Curvilinear relationships of PA and sedentary time with BMI and weight status were estimated using non-parametric smooth terms in GAMMs, which were modeled using thin-plate splines (29). Smooth terms failing to provide sufficient evidence of a curvilinear relationship (based on AIC) were replaced by simpler linear terms. Separate GAMMs were run to estimate PA/sedentary time by study site and by gender interaction effects (two-way and three-way interactions). The significance of interaction effects was evaluated by comparing AIC values of models with and without a specific interaction term. An interaction effect was deemed significant if it yielded a >2-unit smaller AIC than the main effect model (30). Significant interaction effects were probed by computing the site- and/or gender-specific association.

As only 2.6% of cases (n=146) had missing data, the data analyses were only performed on complete cases (31). Participants with complete data were more likely to be older (p=.004), hold a tertiary degree (p=.034), and have more valid hours (p=.013) and days of accelerometer wear time (p<.001), hence all regression models were adjusted for these variables. All analyses were conducted in R (R Development Core Team, 2013) using the packages 'car' (32), 'mgcv' (29), 'gmodels' (33) and 'Epi' (34).

Results

Table 2 shows overall and site-specific descriptive statistics for socio-demographic characteristics, BMI, weight status and accelerometer-based measures of PA and sedentary time. The total sample consisted of 5712 participants; 53% were women, 52% had a college or university degree, 77% were working and 64% were living with a partner. Mean age of the total sample was 43 years (SD=12.4), overall mean BMI was 25.8 (SD= 4.9).

Associations of accelerometer-derived measures of PA and sedentary time with BMI and weight status

After adjusting for sedentary time, significant curvilinear associations of average daily minutes of MVPA with BMI ($F_{3.63, 3.63} = 33.76$; p<.001) and weight status ($F_{2.45, 2.45} = 28.85$; p<.001) were observed. These are shown in the two left panels of Figure 1. BMI and the probability of being overweight/obese decreased relatively linearly with an increase of average daily minutes of MVPA from 0 to 40–50 min/day. The estimated effects of MVPA leveled off at higher levels of PA and were nil at >150 min/day of MVPA. However, we need to note that the latter estimates had a high level of uncertainty (large confidence intervals) due to the small number of participants achieving such high levels of activity (Figure 1). No significant associations of accelerometer-derived sedentary time with BMI ($e^b = 3.20 \cdot 10^{-5}$; 95% CI: 0.99, 1.00; p = .271) and weight status ($e^b = 1.0004$; 95% CI: 0.9997, 1.0012; p = .243) were found.

The associations of average accelerometer counts/min with BMI ($F_{3.27, 3.27} = 40.94$; p<.001) and weight status ($F_{2.02, 2.02} = 44.18$; p<.001) were also significant and curvilinear (see right panels of Figure 1), but more uniformly negative across the whole range of values than those observed for daily minutes of MVPA (left panels of Figure 1).

Moderating effects of study site and gender

Study site and gender significantly moderated the associations of PA and sedentary time with BMI (see Table 3) but not with weight status. Stronger negative associations of MVPA and accelerometer counts/min with BMI were observed in men than women in Belgium, Brazil, Colombia, Denmark and Mexico (Table 3 and Figure 2). The opposite was true for the Czech Republic (one site: Olomouc) and the two USA sites (Table 3 and Figure 2): stronger negative associations of MVPA and accelerometer counts/min with BMI were observed in women than in men. No significant associations in men or women were found in Hong Kong, Hradec Kralove (site in Czech Republic), Spain and the United Kingdom. The latter findings cannot be attributed to differences in sample size as the point estimates of the regression coefficients are indicative of smaller (almost nil) effects compared to other sites. The two USA sites were the only study sites to show significant positive associations of sedentary time with BMI. Notably, they were only significant in women (Table 3).

Discussion

Our first aim was to examine the dose-response associations of accelerometer-assessed MVPA, sedentary time and counts/minute with BMI and weight status in adults living in 10 environmentally- and culturally-diverse countries. After controlling for sedentary time and socio-demographic covariates, a curvilinear relationship between MVPA and both BMI and the probability of being overweight/obese was identified. This relationship was almost linearly negative when MVPA levels ranged between 0 and 50 min/day and weakened at higher levels of MVPA. A similar curvilinear association of average accelerometer-based counts/minute with BMI and overweight/obesity was identified, but the relationship was more uniformly negative, with less leveling off at higher levels of average counts/minute. No associations were found between sedentary time and the weight outcomes, after controlling for MVPA.

The curvilinear association identified between MVPA and the weight outcomes is similar to the dose-response model proposed by Pate and colleagues (35) and updated by Haskell and colleagues (36). That model represents a curvilinear relationship between PA and overall health, showing that the strength of the health benefits of PA depends on the baseline activity levels: an initial increase from an inactive to a somewhat active lifestyle provides stronger health benefits than a change from a somewhat active to a very active lifestyle. Furthermore, a comparable curvilinear relationship has been previously identified in relation to risk of coronary heart disease in adults (37). Adults who achieved activity levels consistent with the public-health health guideline of 150 min/week of MVPA had a 14% lower coronary heart disease risk compared with those who did not reach the guidelines; engaging in 300 min/week of MVPA led to a 20% lower risk, but higher levels of PA did not provide additional benefits. A previous study that examined the dose-response relationship of PA with body weight (38), showed an inverse dose-response association between leisure-time PA and obesity in US adults, but only in women. Although not statistically tested, the curve showed evidence of curvilinearity, with the greatest decline in the prevalence of obesity between women who engaged in insufficient levels of PA and those who met the health guideline; a floor effect was observed at higher levels of PA (38).

Within our own findings, the steepest negative association between MVPA and BMI was found when minutes/day of MVPA ranged between 0 and 50 minutes/day. When comparing this amount to the health guideline of 150 minutes of MVPA per week, it seems that more PA (350 minutes/week in this case) is even more beneficial, specifically in the context of weight gain. This is consistent with the guidelines that have been formulated for the prevention of unhealthy weight gain: according to the Institute of Medicine, normal-weight adults should accumulate 60 minutes of MVPA per day to prevent weight gain (39,40). Higher levels of PA may have important additional beneficial effects on fitness or other health outcomes (41). However, one needs to keep in mind that the present results are cross-sectional – therefore, no true dose-response relationships can be assumed.

The curvilinear relationship of accelerometer-based MVPA with BMI and weight status was confirmed by the comparable associations found for accelerometer-based counts/minute. This is encouraging, as accelerometer counts are a cumulative measure of PA that is not susceptible to cut point categorizations based on limited consensus. Although the shape of the curves was similar, less attenuation was visible at higher levels of counts/minute than at higher levels of MVPA. This might be due to the fact that counts/minute is a more general measure, capturing every accelerometer movement that exceeds zero. Hence, light-intensity activities and counts associated with sedentary time (categorized as 100 counts/minute; 28) were included in the total-counts measure. The counts/minute measure likely has a lower level of error, so the associations consequently will be stronger. It is reassuring that similar conclusions can be drawn from the graphs representing the associations of MVPA and counts/minute with BMI and the probability of being overweight.

Except in US women, no associations between sedentary time and the outcomes were found. This is in contrast with previous longitudinal and cross-sectional studies revealing that more time spent in sedentary behavior (predominantly assessed as TV viewing) was consistently associated with higher risk of obesity, even after accounting for PA and other covariates (5,42,43). However, in their review of prospective studies examining associations between sedentary time and health outcomes, Thorp and colleagues (7) concluded that findings on the relationship of sedentary time with BMI and weight gain in adults are inconsistent, with small effect sizes and effects being largely dependent on baseline BMI – suggesting potential reverse causation. Similarly, Proper and colleagues (6) concluded that insufficient evidence was available to draw conclusions on the relationship between sedentary time and weight-related measures. More convincing evidence is available to support the relationship between sedentary time and other health outcomes like premature mortality, all-cause and cardio-vascular disease related mortality, cancer and diabetes (6,7).

Associations of sedentary time with BMI may be weak and inconsistent because BMI is largely dependent on other factors such as energy intake, PA and heredity (44). Furthermore, previous studies that found a significant association of sedentary time with BMI or weight status mainly used self-reported TV viewing time as a proxy of sedentary time, and generally have not reported findings for overall sedentary time. This may have led to biased results because TV viewing is known to be strongly associated with increased energy intake, particularly snacking (7). In addition, the insignificant findings reported here could be due to the fact that accelerometers were used to assess sedentary time. Accelerometry provides an objective measure of sedentary time, which is not susceptible to biases (e.g. social desirability, recall bias) that are inherent in the use of questionnaires, but subjective decisions still need to be made when processing accelerometer data. For instance, counts/minute need to be converted to minutes of sedentary time by using cut points. Although the cut point of ≤100 counts/minute to define sedentary time (28) is widely used, it was not empirically derived and might miss some sedentary activity. Some studies have shown that a higher cut point might be more sensitive to detect sedentary time (45,46). In future studies, it will be informative to use inclinometers – objective, posture-based measures of true sitting or reclining time. Previous studies have used activPAL monitors (Physical Activity Technologies, Glasgow, Scotland) to directly assess posture and thus more accurately capture sedentary time, compared to accelerometers (which primarily capture movement). Inclinometers also provide more accurate measurement of posture due to the placement of inclinometer devices on the thigh rather than on the hip (46). Future (prospective) studies should also focus on the broad range of light-intensity physical activities, in order to find out how these activities relate to weight status and other health parameters. It would be interesting to discriminate between low-light intensity activities and high-light intensity activities, because previous cross-sectional research showed that associations with physical health are stronger for high-light intensity PA than for low-light intensity PA (47,48). Nonetheless, some discussion still exists about which accelerometer-based cut points should be used to define the different types of light-intensity PA (47,48). Finally, further research should take into account the possible importance of breaks in sedentary time, in addition to total sedentary time. Preliminary evidence from cross-sectional studies revealed that breaks in sedentary time are beneficially associated with BMI and waist circumference in adults (49,50).

As a second aim, the possible moderating effects of gender and study site on the associations of MVPA, sedentary time and counts/minute with BMI and weight status were examined. For BMI, there were complex site- and gender-specific findings; for weight status, no such moderating effects were present. In most countries except for Spain, the United Kingdom and Hong Kong, accelerometer-based MVPA and counts/minute were related to BMI, but in some countries stronger associations were found in men, while in others, associations were stronger in women. Depending on site and gender, both linear and curvilinear associations were observed. No previous studies have examined the country-specificity of such associations, but in the large-scale USA study by Seo and Li (38), a curvilinear association between leisure-time MVPA and obesity was found only in women. No clear explanations for the moderating effects that we have identified can be given. Participants living in the countries where no, or only gender-specific, associations were found did not have particularly high levels of MVPA (so they were not located at the higher end of the continuum, where associations attenuated), and as noted in the results section, the findings cannot be attributed to differences in sample size between countries. Perhaps, non-assessed country- or gender-specific dietary patterns play a confounding role here. In future research it will be crucial to further combine data from multiple countries and examine the country- and gender-specificity of the associations, as important culturally-dependent associations may be revealed. If confirmed in future prospective studies, the gender- and country-specific findings identified here may have important implications in the context of formulating PA guidelines to help prevent weight gain.

Although the present study had several strengths, including the large sample size, comparable data collection protocols across 10 countries, use of objective methods to assess MVPA and sedentary time, and application of complex statistical models that allowed for curvilinear associations, some limitations need to be acknowledged. First, IPEN Adult employed a cross-sectional design, precluding inferences about causality. Second, estimates of MVPA and sedentary time that were obtained may not be representative of the total population in the participating countries, since participants were recruited from specific neighborhoods selected on their walkability and income levels. Third, response rates and ActiGraph models used varied across study sites. This may imply sampling biases or other methodological biases across study sites. Fourth, only PA and sedentary time were examined in relation to weight outcomes; a more complete perspective could have been provided if diet-related measures, information on sleep duration and a more precise measure of body fat were included as well. Fifth, a combination of self-report and objective measures were used among countries to determine BMI and weight status: this could have biased the results.

In conclusion, this study provided evidence of a curvilinear association of accelerometer-based MVPA and counts/minute with BMI and weight status in adults living in 10 environmentally and culturally diverse countries. Because the curve attenuated at MVPA levels higher than 50 minutes/day, the currently Institute of Medicine recommendation of 60 minutes/day of MVPA to prevent weight gain in normal-weight adults was supported. No relationship between sedentary time and the weight outcomes was present, so if confirmed in future studies, it seems that no specific guidelines for sedentary time can be formulated, at least not for weight-related health promotion. As this was the first study to examine the country-specificity of these associations, no definite conclusions can be drawn. However, if confirmed in future prospective studies, the relationship between MVPA and BMI may be country- and gender-dependent, which could have important implications for country-specific health guidelines.

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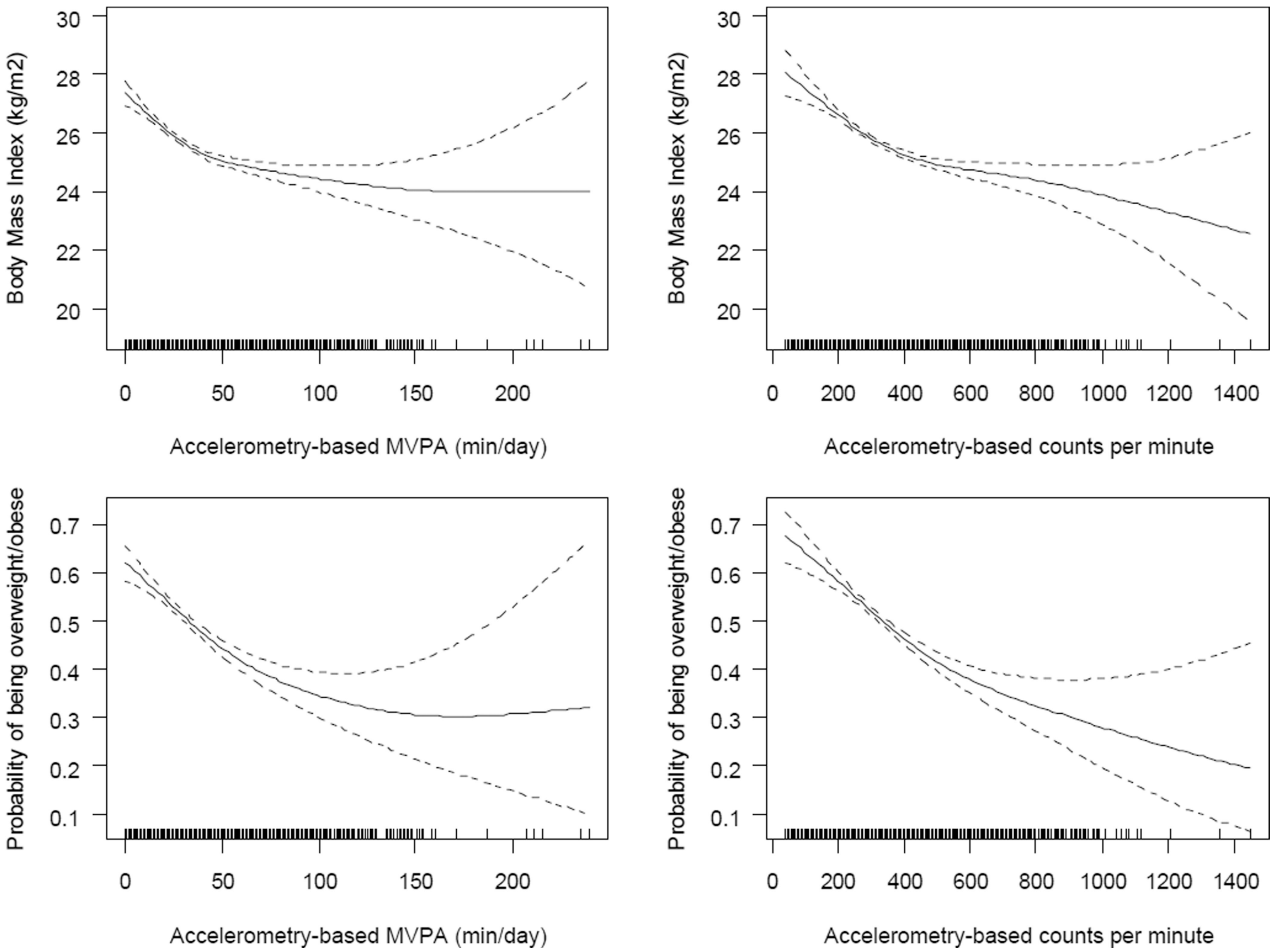

Figure 1. Relationships of accelerometry-based measures of physical activity with body mass index (kg/m^2) and the probability of being overweight/obese

Note. The solid line represents point estimates (and dashed line their 95% confidence intervals) of body mass index (kg/m^2) of probability of being overweight/obese at various levels of physical activity. These estimates were computed at average levels of covariates.

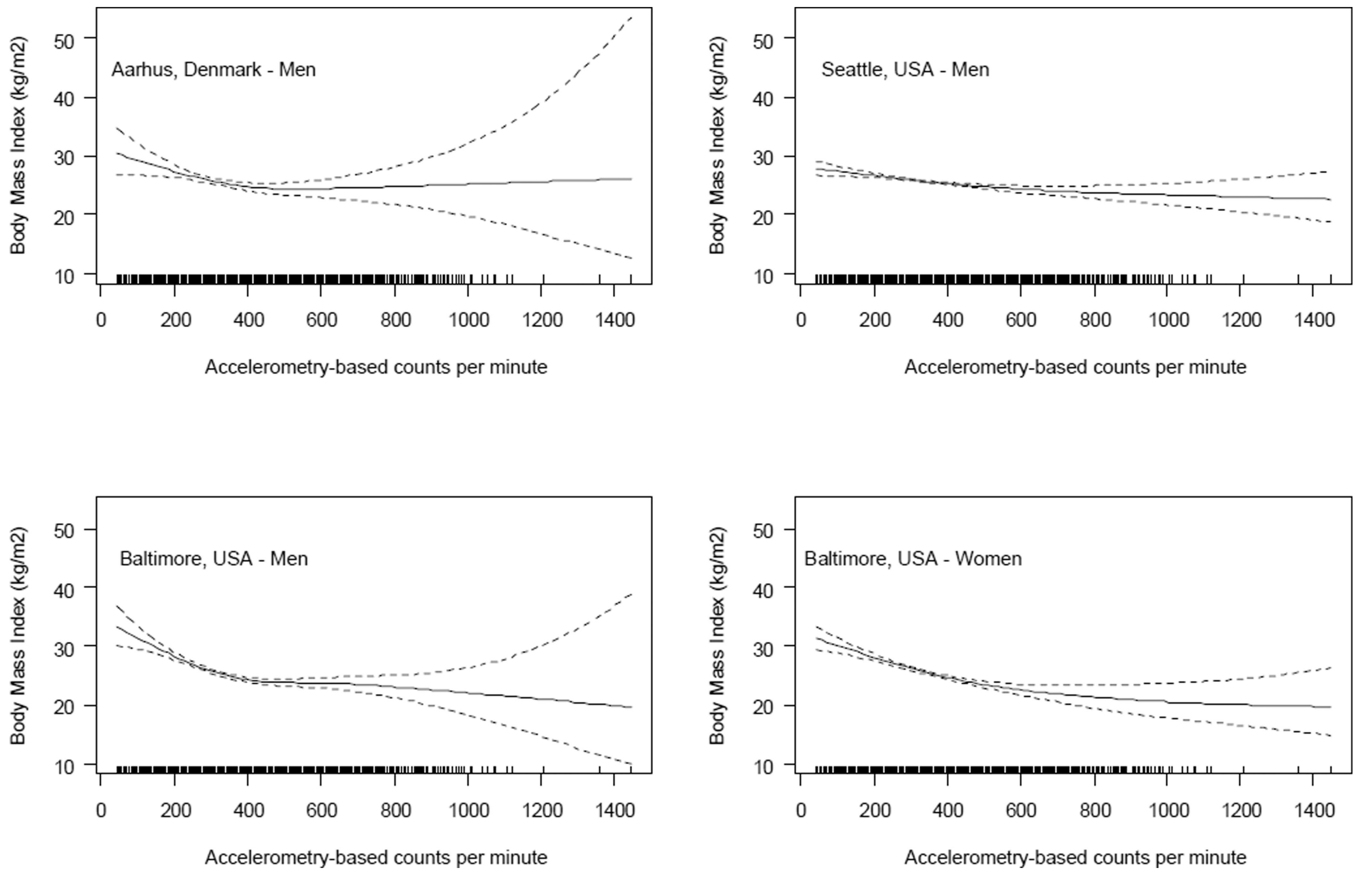

Figure 2. Site- and gender-specific curvilinear relationships between accelerometry-based counts per minute and body mass index (kg/m^2)

Note. The solid lines represent point estimates (and dashed line their 95% confidence intervals) of body mass index (kg/m^2) at various average accelerometry-based counts per minute. These estimates were computed at average levels of covariates.

Table 1

Neighborhood selection criteria and measurement methods for the 10 included IPEN countries

	BEL	BRA	COL	CZE	DEN	HK	MEX	SP	UK	USA
#neighborhoods (NH)/areas/census units	24 neighborhoods	32 census tracts	30 neighborhoods	62 neighborhoods	16 districts	32 tertiary planning units	32 census tracts	Oversampling in different building dates	16 lower super output areas	32 neighborhoods/ 219 block groups
Walkability administrative unit	Statistical sectors	Block group	Block group	Urban districts	Smallest statistical sectors	Tertiary planning units	Census tracts	Not applicable	Output areas	Block group
Walkability index details	GIS: intersection density, residential density Observations: land uses, no retail FAR	GIS: 5 land uses, intersections density (unweighted), residential density, no retail FAR	GIS: 18 land uses, intersection density (unweighted), residential density, retail FAR	GIS: 7 land uses, intersection density (weighted), residential density, retail FAR	GIS: 5 land uses, intersection density, residential density, retail FAR	GIS: intersection density (unweighted), residential density, no land use or retail FAR	GIS: 5 land uses, intersection density (weighted), residential density, retail density	Observations: pedestrian only old town, modern high density down town, suburbs	GIS: 5 land uses, intersection density (unweighted), residential density, no retail FAR	GIS: 5 land uses, intersection density (weighted), net residential density, retail FAR
Walkability criteria	1st, 2nd, 3rd 4th (low), 7th, 8th, 9th, 10th (high) deciles	2nd–3rd (low) and 8th–9th (high)	GIS derived walkability index median split	1st, 2nd, 3rd, 4th (low), 7th, 8th 9th, 10th (high) deciles	GIS derived walkability index median split	GIS derived walkability index High=6.0 to 0.8 with mean=3.0; Low=−1.9 to - 1.5 with mean=−1.8	GIS derived walkability index median split	Build date and pedestrian only areas	GIS derived walkability index all quintiles represented	1st, 2nd, 3rd, 4th (low), 7th, 8th 9th, 10th (high) deciles
Neighborhood income criteria	Median household income (excluding outliers of <€11600 and >€116000): lowest 4 deciles and highest 4 deciles	Mean household income	SES index including household income, car ownerschip, education	SES index including income, level of education, ownership of house, car, computer, telephone, employment status	Median household income: median split	Median household income (below HK$10000/ month=low; above HK$25000 month=high)	Low:1–4, high: 6– 10; out of 12 SES government defined levels by Census Tracts (levels 11 and 12 were excluded due to inaccessibility to such neighborhoods)	Not applicable	16 neighborhoods based on index of multiple deprivation (all high deprivation neighborhoods, deciles 1–6)	2nd, 3rd, 4th (low) 7th, 8th, 9th (high) deciles of household income for each region
Administration mode	In person	In person	In person	In person	Online	Mail	In person	Mail	In person/mail	Mail/online
BMI (measurement mode)	Self-report	In person & self-report	Self-report	Self-report	Self-report	In person & self-report	In person	Self-report	In person & self-report	Self-report

GIS = geographic information system; SES=socio-economic status

Table 2

Overall and site-specific sample characteristics: socio-demographics, body mass index (BMI) and accelerometer data

	ALL SITES	BEL	BRA	COL	CZE		DEN	HK	MEX	SP	UK	USA	
					Site A	Site B						Site C	Site D
Overall N	5712	1050	330	223	258	122	272	269	656	329	135	1198	870
Age, years missing: 0.2% Mean (SD)	43.0 (12.4)	42.8 (12.6)	41.8 (12.7)	45.6 (11.8)	38.6 (14.3)	35.8 (13.6)	39.8 (13.8)	42.3 (12.8)	42.2 (12.6)	39.4 (13.4)	43.6 (13.3)	44.2 (10.9)	46.7 (10.7)
Gender, *%men* missing: 0.04%	47	49	49	32	36	39	39	41	46	40	47	55	48
Education, % missing: 1.0%													
Less than HS	14	4	28	47	23	16	7	36	44	4	39	1	2
HS graduate	34	33	31	36	44	56	42	23	29	33	46	35	30
College or more	52	63	41	17	33	28	51	41	27	63	15	64	68
Work status, *%working* missing: 0.2%	77	80	79	61	78	83	75	63	72	76	64	81	83
Marital status, *%couple* missing: 1.0%	64	73	60	61	60	53	69	56	65	57	46	64	61
BMI, kg/m^2 missing: 0.9% Mean (SD)	25.8 (4.9)	24.2 (3.9)	26.2 (4.3)	25.5 (4.1)	24.6 (3.9)	24.2 (3.6)	24.2 (4.0)	22.6 (3.4)	28.0 (5.0)	23.9 (3.4)	27.2 (5.1)	26.6 (5.4)	27.2 (5.7)
Weight status, % missing: 0.9%													
Underweight *(BMI≤18.4)*	2	3	2	2	3	3	2	9	1	4	2	1	1
Normal *(18.5≤BMI≤24.9)*	48	60	39	50	60	58	64	69	27	63	39	45	37
Overweight *(25.0≤BMI≤29.9)*	34	29	40	35	28	31	27	19	41	28	33	34	40
Obese *(BMI≥30.0)*	16	8	19	13	9	7	7	3	31	5	26	20	22
Sedentary time[a] min/day missing: 0% Mean (SD)	513 (105)	507 (110)	476 (111)	463 (92)	486 (101)	508 (95)	572 (91)	542 (98)	468 (90)	544 (88)	499 (104)	523 (104)	538 (102)

	ALL SITES	BEL	BRA	COL	CZE		DEN	HK	MEX	SP	UK	USA	
					Site A	Site B						Site C	Site D
Moderate PA[a] min/day missing: 0% Mean (SD)	34.0 (23.4)	32.9 (21.3)	29.9 (23.5)	36.3 (25.0)	43.9 (24.2)	42.1 (23.7)	35.0 (20.1)	44.0 (24.6)	30.3 (24.3)	48.0 (26.8)	35.2 (25.7)	33.1 (22.4)	27.1 (19.7)
Vigorous PA[a, b] min/day missing: 0% Mean (SD)	2.3 (5.9)	2.6 (5.9)	1.6 (4.5)	0.7 (2.9)	3.2 (7.7)	3.0 (6.3)	4.6 (8.7)	0.9 (2.3)	0.9 (3.0)	3.0 (7.3)	1.6 (3.5)	3.1 (6.9)	2.1 (5.4)
Median (IQR)	0.1 (1.7)	0.3 (2.3)	0.0 (0.7)	0.0 (0.1)	0.3 (2.5)	0.3 (2.9)	1.1 (4.9)	0.0 (4.1)	0.0 (0.3)	0.2 (2.6)	0.0 (0.9)	0.3 (3.0)	0.1 (1.3)
MVPA[a, b] min/day missing: 0% Mean (SD)	36.3 (25.4)	35.5 (23.5)	31.5 (24.5)	37.0 (26.4)	47.1 (27.7)	45.1 (25.9)	39.7 (23.3)	44.9 (25.3)	31.2 (25.2)	51.0 (29.5)	36.7 (27.3)	36.3 (24.9)	29.2 (22.0)
Median (IQR)	31.4 (31.1)	31.2 (26.7)	25.2 (27.8)	31.8 (28.9)	44.2 (35.4)	41.6 (35.7)	34.8 (29.4)	42.2 (33.3)	25.5 (28.9)	44.8 (33.0)	32.0 (32.9)	31.2 (31.0)	23.4 (29.2)
Accelerometer Counts (counts/min)[a] Mean (SD)	351 (145)	359 (144)	345 (149)	350 (142)	415 (152)	391 (132)	343 (137)	341 (126)	342 (139)	390 (153)	364 (165)	354 (146)	313 (136)
Valid days of wear time[a] Mean (SD)	6.5 (1.1)	6.7 (1.1)	6.7 (1.0)	6.6 (1.0)	6.2 (1.2)	6.2 (1.4)	7.0 (0.8)	5.9 (1.0)	5.7 (1.0)	6.5 (0.8)	6.6 (1.0)	6.7 (0.8)	6.7 (1.2)
Average valid hours per day of wear time[a] Mean (SD)	14.5 (1.4)	14.7 (1.3)	14.0 (1.3)	13.9 (1.2)	13.9 (1.4)	14.2 (1.3)	14.9 (1.1)	14.4 (1.4)	14.0 (1.4)	15.0 (1.1)	14.6 (1.2)	14.7 (1.3)	14.8 (1.4)

Notes: Site A: Olomouc, B: Hradec Kralove, C: Seattle, D: Baltimore; HS=high school; PA=physical activity; MVPA = moderate-to-vigorous physical activity; SD = standard deviation; IQR = inter quartile range;

[a]accelerometer-based measures;

[b]skewed variables, so both mean and median are reported

Table 3

Site- and gender-specific associations of accelerometer-based physical activity measures with body mass index (BMI)

Correlate	Associations in men		Associations in women	
	eb (95% CI)	p	*eb* (95% CI)	p
Model 1 (MVPA + sedentary time)				
MVPA (min/day)				
Belgium	**0.9993 (0.9988, 0.9999)**	**.023**	**0.9990 (0.9983, 0.9998)**	**.011**
Brazil	**0.9989 (0.9980, 0.9998)**	**.023**	0.9993 (0.9980, 1.0005)	.257
Colombia	**0.9987 (0.9976, 0.9999)**	**.037**	0.9996 (0.9984, 1.0008)	.491
Czech Republic (site A)	0.9990 (0.9977, 1.0002)	.101	**0.9987 (0.9976, 0.9999)**	**.032**
Czech Republic (site B)	1.0005 (0.9986, 1.0025)	.595	0.9990 (0.9975, 1.0005)	.206
Denmark	**0.9985 (0.9987, 0.9997)**	**.017**	0.9995 (0.9984, 1.0007)	.439
Hong Kong	0.9999 (0.9987, 1.0010)	.814	1.0004 (0.9993, 1.0016)	.493
Mexico	**0.9989 (0.9983, 0.9996)**	**.001**	0.9999 (0.9980, 1.0009)	.900
Spain	0.9999 (0.9992, 1.0007)	.835	0.9994 (0.9985, 1.0009)	.247
United Kingdom	1.0003 (0.9988, 1.0018)	.735	0.9991 (0.9972, 1.0011)	.385
USA (site C)	**0.9989 (0.9984, 0.9994)**	**<.00 1**	**0.9975 (0.9968, 0.9981)**	**<.00 1**
USA (site D)	**0.9992 (0.9985, 0.9999)**	**.028**	**0.9969 (0.9962, 0.9977)**	**<.00 1**
Sedentary time (min/day)				
Belgium	1.0001 (0.9999, 1.0002)	.211	0.9999 (0.9998, 1.0001)	.469
Brazil	1.0001 (0.9999, 1.0002)	.588	0.9999 (0.9998, 1.0001)	.624
Colombia	0.9999 (0.9996, 1.0001)	.421	0.9999 (0.9996, 1.0001)	.347
Czech Republic (site A)	1.0002 (0.9999, 1.0004)	.204	1.0001 (0.9999, 1.0004)	.297
Czech Republic (site B)	1.0002 (0.9998, 1.0005)	.342	1.0002 (0.9999, 1.0005)	.176
Denmark	1.0001 (0.9999, 1.0004)	.313	0.9994 (0.9997, 1.0002)	.665
Hong Kong	1.0000 (0.9998, 1.0003)	.826	0.9999 (0.9997, 1.0002)	.489
Mexico	0.9999 (0.9998, 1.0000)	.319	0.9998 (0.9997, 1.0000)	.080
Spain	1.0001 (0.9999, 1.0003)	.370	1.0001 (0.9998, 1.0003)	.640
United Kingdom	1.0001 (0.9998, 1.0004)	.539	1.0002 (0.9999, 1.0006)	.231
USA (site C)	1.0001 (0.9999, 1.0002)	.145	**1.0001 (1.0000, 1.0003)**	**.023**
USA (site D)	1.0000 (0.9999, 1.0001)	.966	**1.0002 (1.0000, 1.0003)**	**.022**
Model 2 (accelerometer counts)				
Counts/min				
Belgium	**0.980 (0.967, 0.993)**	**.003**	0.985 (0.969, 1.002)	.083
Brazil	**0.975 (0.953, 0.998)**	**.033**	1.004 (0.977, 1.032)	.780
Colombia	**0.967 (0.937, 0.997)**	**.033**	1.003 (0.971, 1.037)	.850
Czech Republic (site A)	0.973 (0.943, 1.005)	.095	**0.965 (0.937, 0.994)**	**.018**
Czech Republic (site B)	1.010 (0.951, 1.073)	.745	0.965 (0.926, 1.007)	.098
Denmark	**F(2.00, 2.00) = 4.62#**	**.010**	0.987 (0.958, 1.017)	.386
Hong Kong	0.995 (0.962, 1.028)	.745	1.028 (0.993, 1.065)	.114
Mexico	**0.974 (0.958, 0.991)**	**.003**	1.012 (0.990, 1.036)	.283

Correlate	Associations in men		Associations in women	
	eb **(95% CI)**	**p**	***eb*** **(95% CI)**	**p**
Spain	0.998 (0.976, 1.022)	.895	0.984 (0.959, 1.008)	.193
United Kingdom	0.993 (0.963, 1.024)	.648	0.967 (0.926, 1.013)	.165
USA (site C)	**F(1.71, 1.71) = 15.92#**	**<.00 1**	**F(3.26, 3.26) = 28.34#**	**<.00 1**
USA (site D)	0.985 (0.961, 1.001)	.071	**F(2.32, 2.32) = 35.64#**	**<.00 1**

Notes. All models adjusted for socio-demographic covariates and accelerometer wear time;

e^b antilogarithm of regression coefficient, interpreted as the proportional increase in body mass index associated with a 1 unit increase on the predictor; 95% CI = 95% confidence intervals; MVPA = moderate-to-vigorous physical activity; site A = Olomouc; site B = Hradec Kralove; site C = Seattle; site D = Baltimore;

#relationship is curvilinear (F-ratio and significance of non-parametric smooth regression term); Values in bold indicate significant relationships at a probability level of 0.05.